

Soft QCD path to the mass hierarchy

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The study of the quantization of the QCD string with the helix structure [1] is put into the context of a decades-long discussion opposing the probabilistic and the deterministic interpretations of the quantum theory. The recent evolution of the string fragmentation model (to a large extent driven and confirmed by the empirical evidence), towards the deterministic point of view is recounted: the notion of causality not only paves a way to the study of mass hierarchy, it also resolves a long-standing ambiguity about the nature of the so-called Bose-Einstein correlations [2]. Two directions for the further development of the model are outlined: 1/ the relation between the ordered emission of field quanta and the spin of the emitting particle, 2/ the relation between the topological properties of the QCD string and the emergence of new particle types (quantum numbers).

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I. INTRODUCTION

The absence of predictions concerning the particle mass hierarchy is a commonly accepted feature of the probabilistic quantum theory. The fact that there is a possibility to develop a quantum model which does provide a key to the mass hierarchy therefore may come as a surprise, in particular when the novel feature stems directly from the integration of the causality constraint in the model. It is also unusual to start a conventions-breaking model development in the domain of the non-perturbative QCD, considered too complex and out of bounds for reliable calculations. Yet this is what has happened in the past decade, practically unnoticed in the shadow of the highly publicized hunt for Higgs boson(s).

II. THE ORIGINS

Experimental high energy physics relies heavily on the semi-classical model of QCD string fragmentation to describe the formation of hadrons and of the hadronic jets observed in the data. The Lund string fragmentation model [3], at the core of a widely used Monte-Carlo event generator Pythia [4], is so successful in this exercise that the modelling is often taken for granted; model development is replaced by tuning of parameters associated with various subcomponents of the modelling. In case the underlying physics picture for some of the subcomponents is inadequate, a systematic untunable discrepancy is observed in the comparison of the model with the data; due to limited number of observables, there is however competition between contributions from different subcomponents and it becomes difficult to identify the main source of the discrepancy. Progress in the modelling is therefore relatively slow under the best of circumstances; once the precision of the modelling of the hadronization becomes acceptable for the subsequent analysis, and in the absence of new ideas, the model becomes practically frozen. This is precisely what happened to the Lund string fragmentation during the LEP era: the model has been put through extensive tuning on the

data samples from the hadronic Z^0 decay; minor changes have been introduced but the original picture of a 1-dimensional string fragmentation completed with a tunnelling process to generate intrinsic transverse momentum of hadrons has been preserved. It has been duly noted that the performance of the model in the transverse region is poor [5] but the tunnelling process has not been particularly blamed for it (the largest discrepancies appear in the tail of p_T distributions). It is perhaps time to reconsider this attitude: at LEP energies, for $p_T < 1$ GeV, the precision of the modelling is well below 10% for LEP data; at LHC-Run1 energies, the discrepancies reach 20-30% in the same region. As far as the intrinsic hadron transverse momentum is concerned, are there alternatives to tunnelling?

III. HELIX-SHAPED QCD STRING AND LEP DATA

The first and most important step in the replacement of the tunnelling has been suggested by Andersson et al [6]. The study has been primarily motivated by the question of regularization of the end of the parton shower: on the basis of the requirement of helicity conservation in the gluon emission, and as a result of the study of optimal packing of soft gluons in the phase space, the authors concluded that the QCD field created by a pair of colour connected partons should acquire a helical shape and, as a consequence, a non-zero transverse extension. The observation that the gluon emission cannot proceed via a collinear gluon emission and that the consecutive emissions are probably ordered in azimuthal angle has several highly non-trivial implications:

- the emitting/absorbing parton (quark) acquires an effective mass and angular momentum (the cyclical interaction with the field becomes a mass generating mechanism)
- in the fragmentation process, the string tension operates in 3 dimensions and generates the intrinsic transverse momentum of hadrons (replacing tunnelling)
- the helix shape of the string is translated into correlations between transverse and longitudinal components of the hadron momenta.

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The azimuthal ordering of hadrons (following the shape of the helical string) and the correlations between longitudinal and transverse components of hadron momenta should be experimentally observable, as well as modifications of the inclusive p_T spectra. There is however a certain ambiguity concerning the shape of the helix : the phase-space distance between soft gluons forming the colour chain has both longitudinal and transverse components - in Δy (rapidity) and $\Delta\phi$ (azimuthal angle) . The initial search for evidence of azimuthal ordering of hadrons has been done for a helix winding proportional to the rapidity difference between hadrons and no clear signal has been observed [7]. The comparison of an alternative helix parametrization (with winding density proportional to the energy density of the string) has been more successful - it has been shown that the helix fragmentation significantly improves the agreement with the data in observables based on the transverse momentum [8]. The most significant improvement occurs in $\langle p_T \rangle$ vs. x_P (average p_T as function of scaled momentum) which measures precisely the sort of correlation which distinguish the helical string based fragmentation from uncorrelated transverse momentum generation in the standard Lund string fragmentation. The study of inclusive spectra in hadronic Z^0 decays at LEP is a first, admittedly indirect, evidence in favour of the model of helical QCD string.

IV. HELIX-SHAPED QCD STRING AND LHC DATA

A further piece of evidence has been provided by the ATLAS Collaboration which found evidence of azimuthal ordering of hadrons in minimum bias events with minimal acollinear jet activity [9]. The effect can be partially reproduced by a modified Pythia fragmentation routine incorporating the helix string shape [10]. The size of the measured effect is larger than the one expected for direct hadrons - the data suggest the decays of resonances carry, to some extent, the memory of the generating string field. It seems straightforward to extend the fragmentation model to include the decays of short-lived resonances which can be viewed as a continuation of the string fragmentation process, but such an extension destroys the good agreement between the model and the LEP data in the low p_T region: the model produces too many soft hadrons. There seems to be some kind of a natural cut-off in the production of soft hadrons which can be related to quantum effects which are not explicitly included in the model. Somewhat unexpectedly, the solution to the problem comes from the analysis of the space-time properties of the helical string.

V. HELIX-SHAPED QCD STRING AND CAUSALITY

The “folding” of the 1-dimensional QCD string into a 3-dimensional object brings a new feature into the modelling : the possibility to create a causal connection between adjacent string breakups (which are strictly causally disconnected in the Lund string fragmentation). It seems to be an excellent idea on its own to integrate the cross-talk between breakup

vertices into the model but the result by far exceeds the expectations : it literally propulses the model on a qualitatively new level. It is somewhat difficult to understand how a narrow resonance can emerge from random uncorrelated string breakups in the standard Lund string fragmentation; with the causality restored, the quantization pattern describing the light mesons appears rather naturally [1]. Under the causality constraint, the longitudinal momentum decouples from the transverse mass of hadrons which becomes the quantized quantity (the mass of hadron depends on the transverse properties of the string only). The parameters describing the shape of the QCD field can be extracted from the mass spectrum of light pseudoscalar mesons with a precision of $\sim 3\%$. Furthermore, the transverse size of the string obtained through this fit agrees with estimates obtained from the fit of the glueball spectrum in topological QCD [11]. However, the most stringent evidence for the helical winding of the string comes from the analysis of 2-particle correlations.

VI. HELIX-SHAPED QCD STRING AND 2-PARTICLE CORRELATIONS

The quantization rule derived from the spectrum of light mesons defines the ground state hadron (pion) as a piece of helicoidal string with phase difference of $\Delta\Phi \sim 2.8$ rad. If a helix string with regular, or slowly varying winding fragments into a chain of ground state charged hadrons, the model predicts emergence of a correlation pattern characterized by the excess of close like-sign pairs: the quantum threshold for the production of adjacent (unlike-sign) hadrons depletes the low Q region while a sort of Bose-Einstein condensate emerges from the association of closest like-sign particles (with phase separation of 2 times 2.8 rad ~ 0.7 rad $\ll 2.8$ rad). The chain of n ground state hadrons is characterized by mass

$$m(n) \leq n \cdot 0.19 \text{ GeV}. \quad (1)$$

The analysis of ATLAS minimum bias events [2] finds a very good agreement between the data and the model predictions; it seems the so-called Bose-Einstein correlations stem entirely from the coherent production of ground state hadrons. Thus the deterministic variant of the helix string fragmentation accomplishes what several decades of intensive studies of the effect did not achieve - it discards the hypothesis of incoherent origin of correlations, and provides a recipe to reproduce the effect in MC models, with parameters fully constrained by the fit of the mass spectrum of light mesons.

VII. HELIX-SHAPED QCD STRING AND THE QUANTUM THEORY OF MOTION

Profound similarities can be found between the quantized helix string model and the quantum theory of motion [12]. The quantum potential of the later corresponds to the effective transverse string shape; the helix string model takes a step further and associates the quantum potential with the interaction

of the charged particle with the field quanta. Most of the argumentation developed in [12] applies directly to the helix string model. In particular, it has been argued that the quantum potential defines the non-classical but unique particle trajectory satisfying the principle of uncertainty.

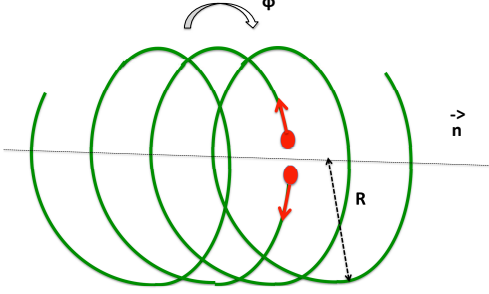


FIG. 1. The breakup of the helix-shaped string.

Let's look in more detail on the parton trajectory in the quantized helix string model. Imagine the helical string breaking by the $g \rightarrow q\bar{q}$ process (Fig. 1); the quarks are treated as massless and their initial momentum is considered negligible. Under the action of the string tension (surrounding field) the quarks follow the curved trajectory which is non-classical: they are spinning around the direction of string axis acquiring "macroscopic" longitudinal momentum, angular momentum and effective mass; the average transverse momentum is vanishing. Let's set the starting parton configuration at $t=0$, with string axis passing through the origin and pointing along \vec{n} . After a time interval Δt , the position of the parton becomes

$$x(\Delta t) = [\Delta t, \Delta t \beta c \vec{n}, \vec{R} \exp^{i\omega \Delta t}] \quad (2)$$

where vector \vec{R} points in the direction of the helix trajectory at the origin (breakup point), and $\vec{n} \cdot \vec{R} = 0$; the momentum acquired by the parton via the interaction with the string (field) is

$$p(\Delta t) = \kappa c [\Delta t, \Delta t \beta c \vec{n}, \vec{R} (\exp^{i\omega \Delta t} - 1)] \quad (3)$$

where κ stands for the string tension, and $\beta = \sqrt{1 - (R\omega/c)^2}$. The helicity factors in the exponent are neglected for the moment.

The particle appears on the classical trajectory (= measured position + $\beta c \Delta t \vec{n}$) just once per the period, for $\omega \Delta t = k 2\pi$, $k=1,2,\dots$. The corresponding string action can be calculated ($k=1$):

$$x(\Delta t) \cdot p(\Delta t) - x(0) \cdot p(0) = \kappa c \frac{(\Delta t)^2}{\gamma^2} = \kappa c \tau^2 \quad (4)$$

where $\tau = \frac{2\pi}{\omega \gamma}$ stands for the invariant period of parton rotation (spin).

It is possible to calculate τ from the radius of the helix string (obtained independently from the fit of light pseudoscalar mesons [1], and from the shape of 2-particle correlations [2], for $\kappa = 1 \text{ GeV/fm}$):

$$\tau = \frac{2\pi R}{c} = (0.427 \pm 0.013) \text{ fm}/c \quad (5)$$

which leads us to the estimate

$$\kappa c \tau^2 = \kappa (0.183 \pm 0.01) \text{ fm}^2/c \simeq \hbar. \quad (6)$$

(Equivalent result is obtained from the integral of the string action using the Lagrangian constructed from the field potential and the kinetic energy of the parton).

VIII. HELIX-SHAPED QCD STRING AND THE SPIN OF PARTONS

We arrive at the point where the quantized helix string model (more specifically, the accumulated empirical evidence accompanying its development) does not leave other choice but to associate the angular momentum stemming from the interaction with the field quanta with the spin of the emitting (absorbing) parton.

As stated in the introduction, it is highly unusual to attempt to develop the spin model in the domain of non-perturbative QCD. It is nevertheless possible that the study of hadronization is where the problematics becomes most accessible from the experimental point of view, due to the trace of the ordered gluon emission preserved by the confinement.

The interpretation of the spin in terms of gluon and photon emission/absorption can actually help to understand some non-intuitive properties of the spin.

As explained in Section III, the helicity conservation requires that the emitting parton and the emitted gluon have to go apart. In the transverse plane, the emission is equivalent to a phase change along the effective helix-like trajectory of the emitting quark $\phi \rightarrow \phi + d\phi$. The emitted gluon acquires transverse momentum and phase

$$p_T^g = 2R |\sin(d\phi/2)| \quad (7)$$

$$\phi^g = \phi + d\phi/2 \quad (8)$$

and the quark, in virtue of momentum conservation, carries the recoil transverse momentum $p_T^q \exp^{i\phi^q + \pi}$.

In a purely mathematical approach, fancy effects can be obtained with spinors using $d\phi > \pi$, in particular $d\phi = 2\pi$ which seemingly reverts the parity of the particle state. The physics case of the gluon or photon emission is different: the range of the possible phase change for a single emission is limited by $|d\phi| \leq \pi$, with positive/negative values distinguishing the positive/negative helicity (right-handed and left-handed emission). It takes at least two subsequent emissions (or an emission and an absorption) of field quanta to accomplish a phase change of 2π for the emitting particle, for which the recoil vanishes; the result is nevertheless not an identity since the particle moves along the longitudinal direction of the string, too.

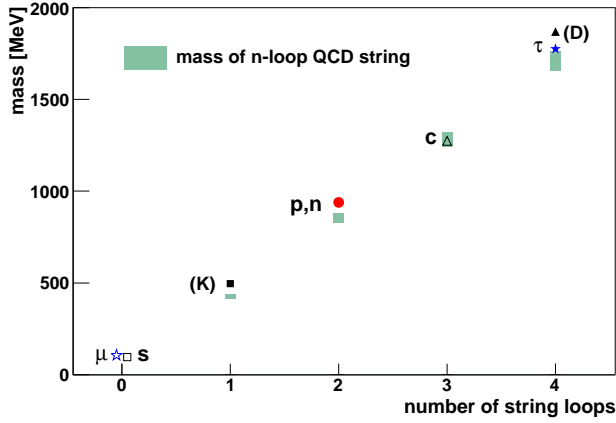


FIG. 2. The mass spectrum of particles [13] carrying a new quantum number compared with the mass of a helix-shaped QCD string with parameters derived from experimental data. The open and bound quark states are included (s-K, c-D).

IX. HELIX-SHAPED QCD STRING AND THE EMERGENCE OF NEW QUANTUM NUMBERS

In [1], the mass spectrum of light mesons emerging from the quantization pattern of the helix-shaped QCD string has been discussed. But there seems to be even deeper connection between the topology of the helix-shaped QCD string and the mass hierarchy : the new particle types (quantum numbers) seem to emerge in mass interval which corresponds to the mass of a single loop of the helix-shaped string. The mass stored in 1 loop of the helical QCD string is, according to the current best estimates,

$$m(1 \text{ loop}) = 2\pi\kappa R = (0.427 \pm 0.013)\text{GeV}. \quad (9)$$

Fig. 2 shows the comparison of the mass of N-loops with the mass of (lightest) particles carrying a new quantum number.

The picture suggests these quantum numbers are related to the topological knotting of the string across the loops with a binding energy of $\sim 70\text{-}100$ MeV.

X. FINAL REMARKS

The model of helix-shaped QCD string provides a bridge between several seemingly disconnected areas of research in the particle physics (mass spectrum of hadrons, spin physics, particle correlations). It is doing remarkably well in some of notoriously problematic domains of the particle production (description of intrinsic hadron transverse momentum, Bose-Einstein correlations). In the frame of the model, a close relation between causality and quantum properties can be established. The resulting phenomenological construction is in very good agreement with experimental measurements. There is a large variety of complementary measurements which can be performed in order to test the model: verification of the prediction of a p_T threshold in the production of direct hadrons, study of the asymmetry of particle correlations with respect to the orientation of string, the link between azimuthal ordering and the study of ordered hadron chains, polarization studies etc. In the author's opinion, there is already enough experimental evidence to demonstrate the power of the deterministic approach to the quantum effects and its superiority with respect to the purely probabilistic interpretation of the quantum physics, but it is also clear there is still much work to do to reconcile the physics community on this subject. Two areas of possible further development of the model from the phenomenological point of view are outlined (the spin physics and the topological interpretation of mass hierarchy).

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